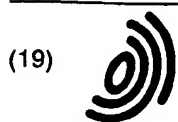


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PCT2109



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(11) EP 1 276 188 A2

(12) EUROPEAN PATENT APPLICATION

(43) Date of publication:  
15.01.2003 Bulletin 2003/03

(51) Int Cl.7: H01S 5/183

(21) Application number: 01108647.7

(22) Date of filing: 05.04.2001

(84) Designated Contracting States:  
AT BE CH CY DE DK ES FI FR GB GR IE IT LI LU  
MC NL PT SE TR  
Designated Extension States:  
AL LT LV MK RO SI

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(54) A vertical-cavity surface-emitting laser with enhanced transverse mode stability and polarization stable single mode output

(57) A vertical-surface-emitting laser comprises: a first reflector means and a second reflector means arranged to define a laser resonator extending along a longitudinal direction and along transverse directions, a laser active region located between the first and second reflector means, a metal layer at the first or second reflector means and patterned to form a radiation emission window, and a phase matching layer arranged within the resonator and having an optical thickness adapted to

transversely pattern a reflectivity of the first and/or second reflector means. The VCSEL device may further comprise an aperture formed between the first and second reflector means. The mode selectivity of the VCSEL is substantially determined by a reflectivity difference defined by the transverse dimensions of the radiation emission window. Moreover, one linear polarization state is stabilized by breaking the cylindrical symmetry of the VCSEL.

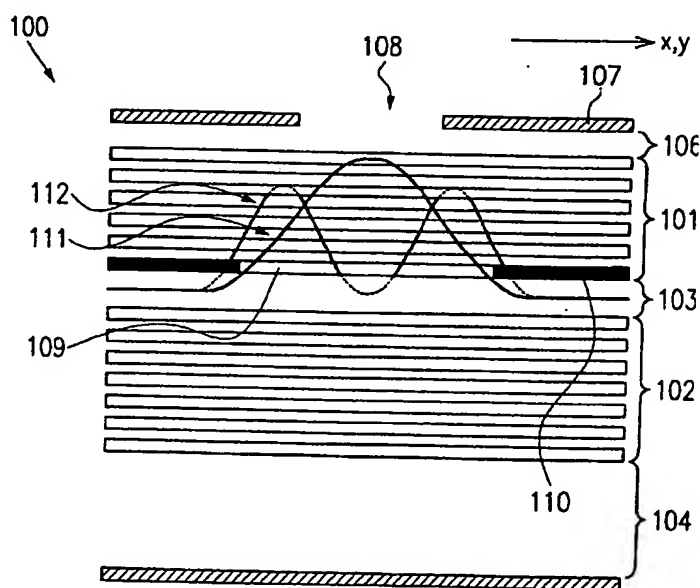


FIG. 1

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## Description

[0001] The present invention relates to a vertical-cavity surface-emitting laser (VCSEL) comprising a first reflector means and a second reflector means arranged to define a laser resonator extending along a longitudinal direction and along transverse directions, a laser active region located between the first and second reflector means, a phase matching layer arranged within the laser resonator, and a metal layer at the first and second reflector means and patterned to form a radiation emission window, wherein an optical thickness of the phase matching layer is adapted to transversely pattern a reflectivity of the first and/or reflector means. Moreover, the present invention relates to a VCSEL having the above-identified features, wherein one of two linear polarization directions is stabilized.

[0002] Semiconductor laser devices are steadily gaining in importance in a plurality of industrial applications. In particular, in the fields of gas spectroscopy, sensing, coupling of laser light into optical fibers, pumping applications and in communication systems requiring a high transmission rate, semiconductor laser devices with high spectral purity, i.e. with single mode radiation in the longitudinal as well as the transverse directions are highly desirable. Due to the short resonant cavity (vertical cavity), typically in the range of one lambda of the emitted wavelength, VCSEL devices generate a radiation in the fundamental longitudinal radiation mode. The transverse extension of the cavity of a VCSEL, in general, is considerably larger than the longitudinal extension of the cavity, and hence a plurality of transverse modes may appear in the emitted laser beam. The wavelength of the transverse radiation modes may differ from the wavelength of the fundamental transverse radiation mode (in the following, referred to as "fundamental mode") by tenths of gigahertz (GHz). In applications requiring a high spectral purity, i.e. in applications where the wavelength of the emitted laser light has to be stable and should be emitted in a single transverse radiation mode with a mode suppression of typically 10-30 decibels, so-called single mode devices are employed. Such devices are advantageously used in sensing applications, spectroscopy and pumping due to the spectral purity and are also advantageous in data communication systems due to the lower noise level, better fiber coupling efficiency and decreased dispersion. Hence, great effort has been made to provide single mode VCSEL devices.

[0003] For example, in *IEEE Photonics Technology Letters*, Vol. 9, No. 10, October 1997, pages 1304-1306, a VCSEL is disclosed comprising one or more oxide layers formed by selective oxidation in a Bragg mirror. This oxide layer serves as a current aperture as well as an optical aperture restricting the optical cavity in the transverse directions. By means of this oxidation layer, the lowest order radiation mode may be selected. For incorporating the oxide layer into the Bragg mirror, however,

an additional manufacturing process step is required, resulting in increased cost and lower production yield. Moreover, due to the limited lifetime of laser devices having selectively oxidized layers, such laser devices are merely used in the fields of research and development, rather than for industrial applications.

[0004] In *Applied Physical Letters*, Vol. 72, No. 26, June 1998, pages 345-347, a VCSEL device is disclosed having a surface that is treated by means of etching processes to generate a fine structure on top of the surface. This additional structure increases the optical losses of the radiation having transverse radiation modes of higher order, thereby providing selectivity and preferred amplification of the lowest order mode. As in the above case, these devices require an additional process step in manufacturing the device and this additional step of generating said etched structure demands high accuracy and control in both the transverse position and the depth of the structure.

[0005] In *IEEE Photonics Technology Letters*, Vol. 6, No. 3, February 1994, pages 323-325, a VCSEL is described comprising a loss-guided or "anti-guided" structure exhibiting in the area of the distributed Bragg reflector (DBR) side of the mesa structure a higher reflective index than in the DBR area below the mesa. Thereby, increased optical losses of the higher order radiation modes are achieved. The manufacturing of the anti-guided structure, however, requires a second epitaxial growth step resulting in a considerably increased production time and higher costs of such laser devices.

[0006] In many current VCSEL devices, improvements of the performance is obtained by providing electrical and optical confinement. Thus, corresponding apertures are provided in the VCSEL devices, i.e. a material layer comprising an aperture, wherein the material surrounding the aperture exhibits a higher electrical resistance and a higher optical absorption than the aperture to improve the electro-optical characteristics of the device. Selective oxidation, proton implantation, or a combination of both are employed to form a corresponding aperture to enhance output power as well as to attain lower threshold currents, an increased efficiency and a higher spectral purity. A major drawback of this arrangement, however, resides in the fact that a single mode operation of the VCSEL device requires the aperture to be relatively small, typically in the range of 1-5 micrometers, resulting in an considerably increased current density in the aperture which, in turn, significantly reduces device life-time and reliability.

[0007] A further significant disadvantage of single mode VCSEL devices is the undetermined polarization state of the fundamental mode. The fundamental mode of a VCSEL formed on a [100] substrate has substantially two orthogonally polarized components that are spectrally separated by some gigahertz. Due to quantum mechanical fluctuations, an abrupt change of the polarization direction, a so-called polarization flip, is often observed in single mode devices, in particular when

the device is operated within a large injection current range. These polarization flips inhibit accurate measurements or data transmission with low bit error rates.

[0008] Thus, it is an object of the present invention to provide a VCSEL device having high device reliability and a long and improved durability. A further object of the present invention is to provide a VCSEL device capable of emitting in the fundamental radiation mode, wherein polarization flips are significantly reduced.

[0009] According to a first aspect of the present invention, a VCSEL is provided, comprising a first reflector means and a second reflector means arranged to define a laser resonator extending along a longitudinal direction and along transverse directions, a laser active region located between first and second reflector means, a metal layer at the first or second reflector means and patterned to form a radiation emission window, a phase matching layer arranged in the resonator and having an optical thickness adapted to generate a reflectivity difference of the first and/or second reflector means at a resonator region corresponding to the radiation emission window and the residual resonator region, and an aperture formed between the first and second reflector means, wherein a mode selectivity of the VCSEL is substantially determined by reflectivity difference created by the phase matching layer.

[0010] In accordance with the first aspect of the present invention, the optical thickness of the phase matching layer is adjusted to create a significant reflectivity difference between the region covered by the radiation emission window and the residual resonator regions. Preferably, the reflectivity of the residual resonator regions is significantly reduced to favor emission of the fundamental mode having its intensity maximum at a region corresponding to the radiation emission window. Consequently, the selection of the fundamental mode is primarily determined by the lateral extension of the radiation emission window rather than by the aperture as in prior art devices. Accordingly, the size of the aperture may exceed the size of the radiation emission window and may be optimized to provide a minimum required degree of current confinement while at the same time maintaining the current density within a range that does not degrade the reliability of the device. For a VCSEL device having cylindrical symmetry, i.e., having a substantially cylindrical laser resonator, a diameter of the radiation emission window may be made to about 1 - 7  $\mu\text{m}$  to select the fundamental radiation mode, whereas the diameter of the aperture is selected to approximately 2 - 10  $\mu\text{m}$ . Thus, the current density is reduced by a factor of about 2 compared to a prior art device requiring an aperture of 5  $\mu\text{m}$  in diameter to select the fundamental mode.

[0011] According to a further aspect of the present invention, a VCSEL comprises a first reflector means and a second reflector means arranged to define a laser resonator extending along a longitudinal direction and along transverse directions represented by a first trans-

verse direction and a second transverse direction, a laser active region located between the first and second reflector means, a metal layer provided at the first or second reflector means and patterned to form a radiation emission window having a first lateral extension along the first transverse direction and a second lateral extension along the second transverse direction, a phase matching layer arranged in the laser resonator and having an optical thickness adapted to reduce the reflectivity of the first and/or second reflector means at an area not covered by the radiation emission window to select the fundamental transverse radiation mode. The VCSEL is characterized in that the first lateral extension is different from the second lateral extension to cause a direction-dependent loss of the transverse radiation mode.

[0012] As previously explained, VCSEL devices emit linearly polarized light with a weak elliptical component. The direction of the polarization depends on any anisotropies prevailing in the VCSEL device. In a VCSEL device having a cylindrical symmetry with respect to the longitudinal axis, i.e. a VCSEL device having a substantially cylindrical resonator geometry, the anisotropy caused by the crystal directions determines the possible polarization directions. Most of the VCSEL devices are grown on a [100] substrate, which leads to a linear polarization along the [011] or [01-1] crystal direction. Upon varying operation conditions, in particular a variation of the drive current, a spontaneous polarization flip between these two linear polarization directions can frequently be observed. In optical systems employing polarization sensitive components, however the polarization direction of the VCSEL has to be oriented in a predefined direction and has to be stable over a wide range of drive currents. Since the two polarization components of the fundamental mode are spectrally separated by typically 1-20 GHz, the difference in wavelength between the two polarization states is well above the required accuracy for applications such as sensing, pumping, spectroscopy and the like. Moreover, in data communication, a polarization flip introduces additional noise and thus increases the bit error rate. Measurements have shown that the relative-intensity noise can increase by several orders of magnitude in the presence of a polarization flip. Moreover, in wavelength division multiplex (WDM) applications with spectrally closely-spaced channels, a polarization flip might lead to an incorrect signal transmission.

[0013] Due to the different extension of the radiation emission window along the first and second transverse directions, the reflectivity difference created by the phase matching layer is also patterned in accordance with the shape of the radiation emission window. As a consequence, an additional anisotropy is introduced and selectively breaks the cylindrical symmetry within the device. Thus, the radiation losses within the resonator are different for the first and second transverse directions and will therefore favor one of the two polariza-









comprise an aperture (not shown) to appropriately adjust the current density within the laser active region as has been previously explained. Moreover, the geometric shape of the radiation emission window 608 and/or of the aperture may be designed in numerous ways, as was explained with reference to the embodiments depicted in Figure 5. Furthermore, the fine grid 601 may also be employed in combination with the embodiments described with reference to Figures 1-5. With regards to obtaining a maximum output power, the width of a single bar of the fine grid 610 may be selected to have a width in the range of several hundred nanometers to 1  $\mu\text{m}$ , so that as little surface area as possible is "wasted".

### Claims

1. A vertical-cavity-surface-emitting laser (VCSEL) comprising:
  - a first reflector means (101) and a second reflector means (102) arranged to define a laser resonator extending along a longitudinal direction and along transverse directions;
  - a laser active region (103) located between the first and second reflector means (101, 102),
  - a metal layer (107) at the first or second reflector means (101, 102) and patterned to form a radiation emission window (108),
  - a phase matching layer (106) arranged within the resonator and having an optical thickness adapted to transversely pattern a reflectivity of the first and/or second reflector means (101, 102), and
  - an aperture (109) formed between the first and second reflector means (101, 102), wherein a mode selectivity of the VCSEL is substantially determined by a reflectivity difference defined by the transverse dimensions of the radiation emission window (108).
2. The VCSEL of claim 1, wherein a transverse dimension of the aperture along a first transverse direction and/or a transverse dimension of the aperture along a second transverse direction is larger than the transverse dimensions of the radiation emission window.
3. The VCSEL of claim 2, wherein a transverse dimension of the radiation emission window in the first transverse direction is different from a transverse dimension of the radiation emission window along the second transverse direction.
4. The VCSEL of any of claims 1 to 3, wherein the aperture is formed by selective oxidation of an aluminum containing material layer and/or by proton implantation.
5. The VCSEL of claim 1, wherein the radiation emission window is of substantially circular shape with a diameter that is less than a diameter of the aperture.
6. The VCSEL device of claim 5, wherein the diameter of the radiation emission window is in the range of 1-5  $\mu\text{m}$  to select the fundamental radiation mode.
7. The VCSEL of claim 5 or 6, wherein the diameter of the aperture is selected to limit a maximum current density within said aperture.
8. The VCSEL of one of the preceding claims, wherein the phase matching layer is provided in the first and/or the second reflector means.
9. The VCSEL of claim 8, wherein the phase matching layer comprises at least two sub-layers.
10. The VCSEL of claim 9, wherein at least one of the at least two sub-layers is separated from the other one of said at least two sub-layers,
11. The VCSEL of any of the preceding claims, wherein the phase matching layer comprises Ga and/or As and/or Al and/or In and/or P and/or a polymer and/or a dielectric material having an index of refraction greater than 1, and/or silicon nitride.
12. A VCSEL comprising:
  - a first reflector means (101) and a second reflector means (102) arranged to define a laser resonator extending along a longitudinal direction and along transverse directions, represented by a first transverse direction and a second transverse direction,
  - a laser active region (103) located between the first and the second reflector means (101, 102),
  - a metal layer (507) at the first or second reflector means (101, 102), patterned to form a radiation emission window (508) having a first lateral extension along the first transverse direction and a second lateral extension along the second transverse direction, and
  - a phase matching layer (106) arranged in the laser resonator and having an optical thickness adapted to transversely pattern the reflectivity of the first and/or second reflector means (101,



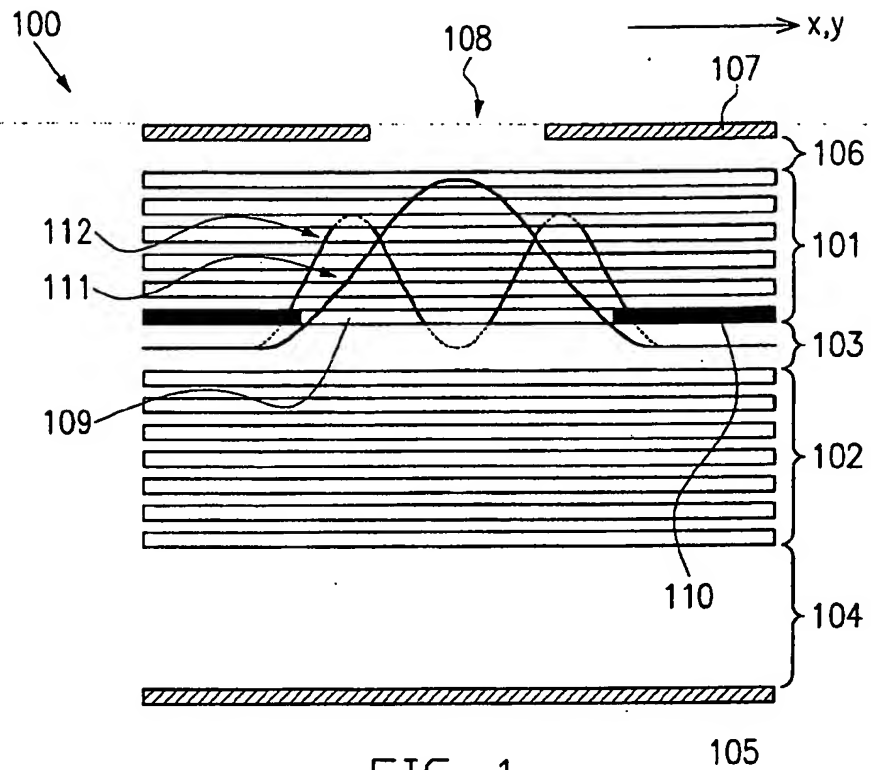


FIG. 1

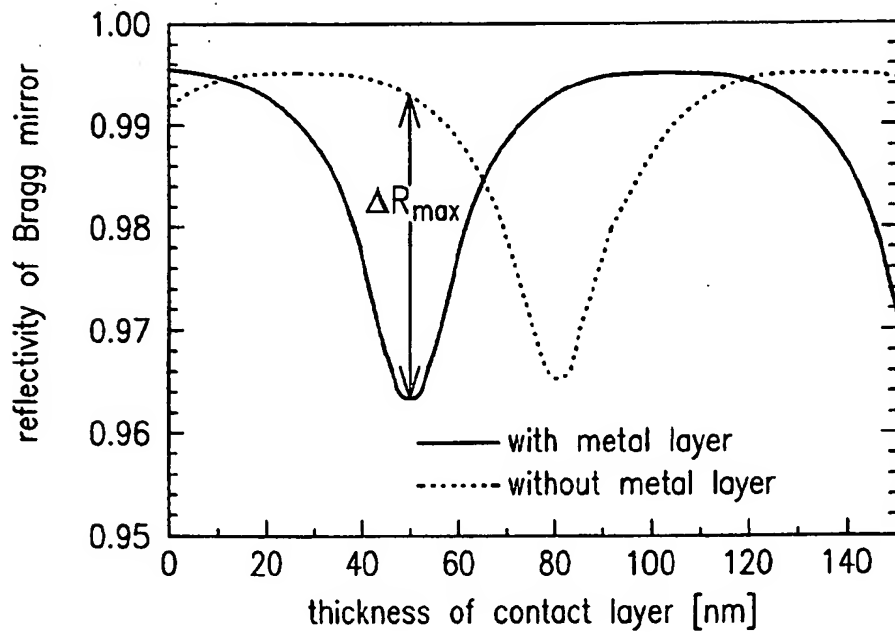


FIG. 2

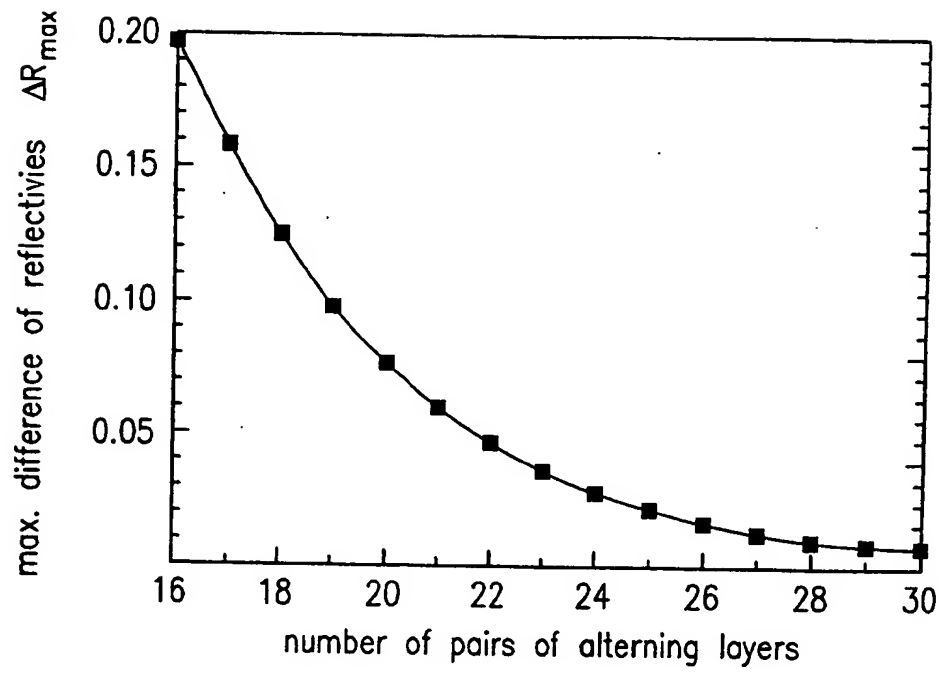


FIG. 3

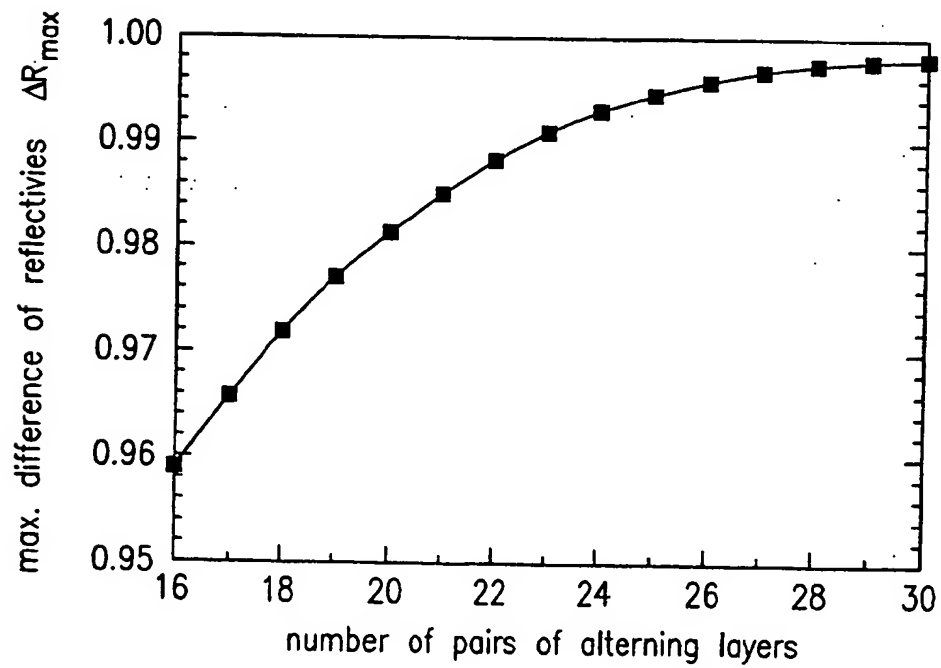
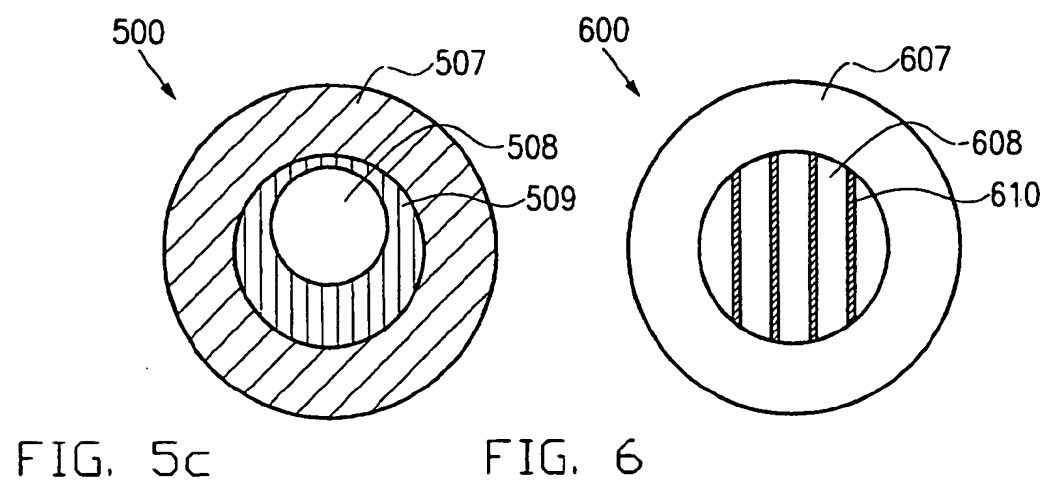
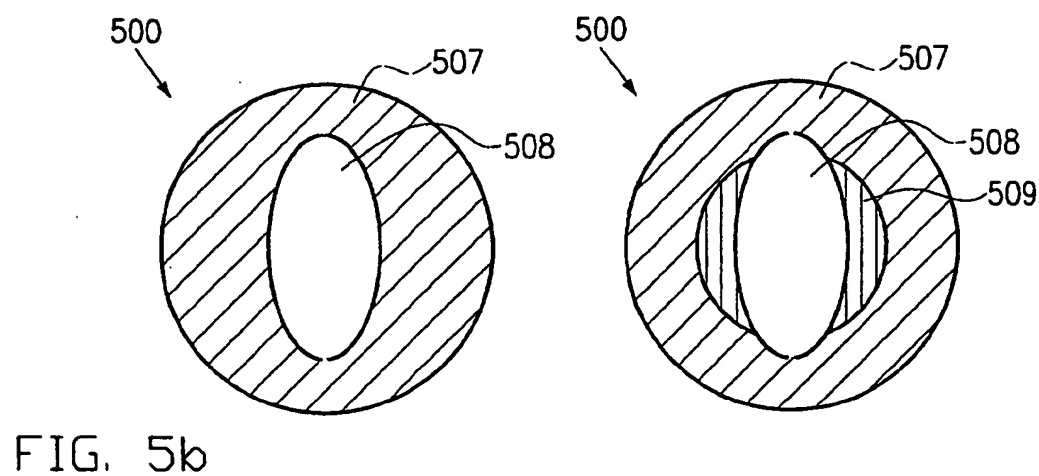
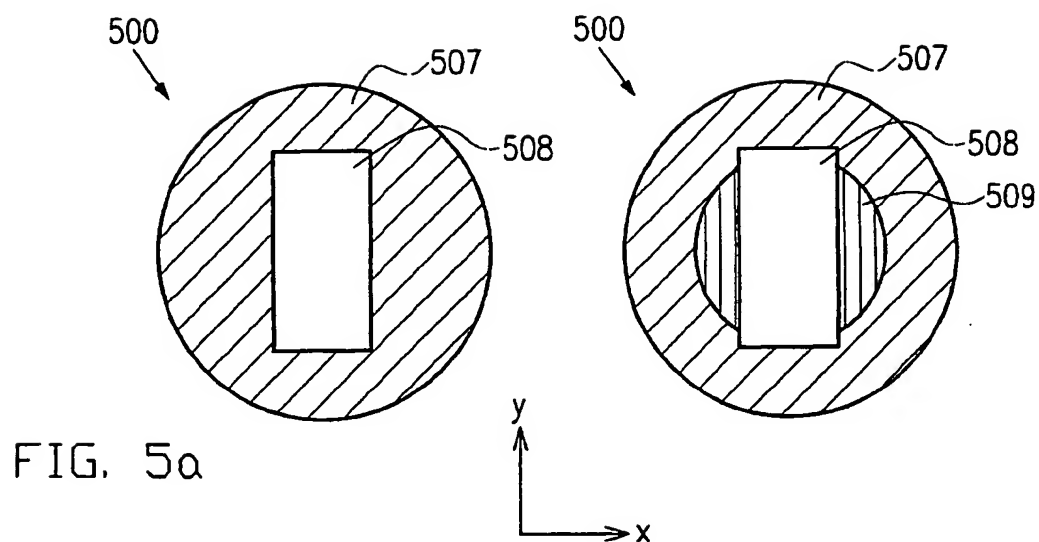


FIG. 4



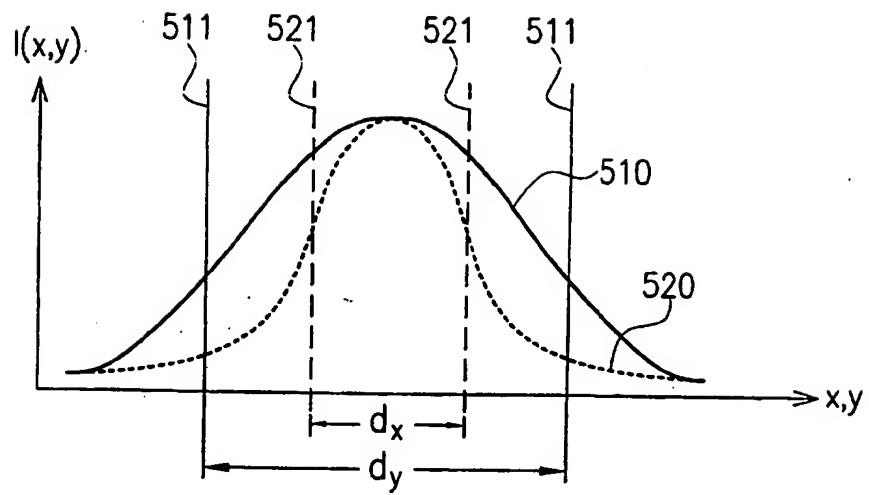


FIG. 5d





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